Space Boosters, Space Satellites

Corrosion prevention systems used on space boosters and satellite systems are controlled by many different criteria related to the expected operating environments and various functional requirements. This can include exposure to a seacoast environment for prolonged periods, periodic immersion in seawater for several days, elevated and cryogenic temperature exposure, exposure to high vacuum and solar radiation in space, and required compatibility with various propellants and operational fluids. In addition, the need for light weight structures, the low safety factors used in component design and the requirement for high reliability places very demanding performance requirements on the protective systems used. For earlier space booster and satellite programs, only one-time use had to be considered, but for programs such as the Space Shuttle most components will be reused many times. Probably the most demanding environmental exposure is that of the Solid Rocket Booster (part of the Space Shuttle propulsion system) where up to twenty reuses are planned. This includes ocean recovery after each flight as shown in Figure 1.

The primary structural materials used for many components in the Space Shuttle propulsion system (see Figure 2) are high strength aluminum alloys. This includes 2219 aluminum alloy for welded structures (including propellant tankage) and 7075 and 2024 aluminum alloys for structures where mechanical joining methods can be used. The protective system used on aluminum surfaces where exterior exposure is the primary concern consists of a chemical conversion coating (MIL-C-5541) to promote paint adhesion, followed by a chromate inhibited epoxy primer [0.025mm (1 mil) thick] and an epoxy top-coat [0.025-0.045mm (1.0-1.8 mils) thick]. This system is used not only on expendable structures for one-time use such as the External Tank in Figure 1, but also on the upper and lower skirt structures of the Solid Rocket Boosters which are recovered from the ocean and reused. This system also provides a good base for bonding thermal protection systems to provide protection from aerodynamic heating and heat from rocket exhaust plumes. To obtain good paint adhesion it has been found extremely important to maintain surface cleanliness between each processing step, particularly following application of the chemical conversion coating. In addition strict compliance to the paint manufacturer's recommendations for drying times and application procedures is required. To insure adequate quality control, the coatings are applied and tested to the requirements of MIL-F-18264.

Where immersion in seawater and component reuse is required, all faying surfaces must be completely sealed (wet lay-up) with a polysulfide sealant meeting the requirements of MIL-S-8802. It is very important that there are no open gaps or voids not completely filled by the sealant, since seawater can be forced into these areas during recovery and will cause a serious corrosion problem that may go undetected. Fasteners should also be installed with wet sealant, and fastener heads must be completely oversealed. One area where these procedures cannot be followed is when electrical bonding is required. For these areas jumper cables are used with the contact surfaces bare but with a complete overseal of polysulfide sealant.

One area of special consideration is corrosion prevention under the polyurethane foam insulation used on the External Tank exterior to prevent excessive cryogenic propellant (liquid hydrogen and oxygen) boil-off during launch preparation and flight. Because of the need for good cryogenic adhesive properties, the paint system previously described cannot be used. It was found also that the bonding primer originally selected to promote adhesion between the tank surface and the spray foam would not adequately protect the 2219 aluminum alloy surface during storage, shipping and launch preparations. Following laboratory tests, the material finally selected for this purpose consists of an epoxy bonding primer with strontium chromate pigment added. This primer provides improved corrosion protective properties under the foam insulation without any significant degredation of cryogenic adhesive properties.

One major area where aluminum alloys are not used is the motor-case of the solid rocket booster (SRB). For this application D6AC low-alloy steel heat treated to 1340-1520 MPa (129-220 ksi) ultimate tensile strength is used. The paint system selected for corrosion protection is a zinc-rich epoxy-polyamide primer [0.038-0.051mm (1.5-2.0 mils) thick] and an epoxy-polyamide top-coat [0.038-0.051mm (1.5-2.0 mils) thick]. The steel surfaces are sand blasted to white metal (Steel Structures Painting Council Specification SSPC-SP6) prior to painting. While this system provides good protection to steel surfaces for prolonged periods of time, the paint is removed (by sand blasting) and re-applied after each flight because of magnetic particle inspection requirements imposed on the motor-case surfaces.

There are a few areas where paint cannot be used to provide corrosion protection. These are the areas where the SRB motor-case segments are joined and where the skirt segments join the motor-case segments. The material used to provide protection here is a heavy duty calcium based grease with special corrosion inhibitors for use in seawater. The grease is carefully applied to all bare areas during assembly, and is removed and re-applied after each flight. The grease protects the surfaces not only during storage and pre-flight operations but also provides exceelent protection for several days ocean exposure during recovery and until joint refurbishing operations can be initiated, which can be several weeks later. The grease can also be diluted with trichloroethane or other solvents and is applied in this form to provide protection to bare motor-case segments during initial rail shipment and also during refurbishment operations after the paint is stripped from used motor cases while they are in storage awaiting subsequent operations.

One area of the SRB program which has been very difficult to protect is the electrical cables and connectors. Since seawater contacting the ends of the stranded electrical wiring will quickly permeate through the wire and prohibit any reuse capability, electrical cables are enclosed in a water-tight jacket of polyether based urethane plastic. This requires bonding of the jacket to the connector at each end of the cable. In addition the stainless steel connectors have a water-tight o-ring seal to prevent the intrusion of seawater. To provide additional protection against inadvertent leakage, the connector pins are coated with a film of heavy duty calcium grease prior to assembly. The female connector sockets are designed so that the grease film is wiped off during insertion of the male pins so that necessary electrical continuity through the connector is maintained.

Since the graphite containing materials used to line the solid rocket motor nozzles appeared to be aggravating corrosion in the SRB aft skirt during immersion in the ocean, sacrificial zinc anodes were added to provide additional protection in this area. This includes zinc anodes for several individual aluminum components, the use of zinc for several non-structural components, and the use of flame sprayed zinc on several aluminum components. In addition, zinc anodes are attached at several locations by divers prior to towing the SRB's back to land for refurbishment. These anodes have reduced significantly the galvanic attack of the aluminum surfaces in the aft skirt of the SRB.

Other alloys used for space booster systems include 304 stainless steel, 321 stainless steel (for welded components), Inconel 718, 6Al-4V titanium, 3Al-2.5V titanium and MP35N nickel-cobalt alloy. While these alloys are inherently corrosion resistant, special treatments are usually required to insure that exposed surfaces are passivated to reduce possible pitting problems. Surfaces exposed to seawater during SRB recovery are flushed with water and refurbished as necessary following each flight to insure that their integrity is not compromised.

One other area which must be carefully considered is the control of stress corrosion. This is caused by the wide-spread use in space booster and satellite systems of high strength alloys which generally have poor resistance to stress corrosion. Several stress corrosion failures have occurred in earlier programs, many of which resulted in significant program impact. Table I is a list of several of these failures. As shown in this table most of the failures have occurred in high strength aluminum alloys and in the precipitation hardening stainless steels. There have also been instances where unique environments were not adequately considered. Careful attention must be paid to specific exposure conditions to insure that proper material selection is made. For instance stress corrosion failure of a beryllium copper spring occurred because it was not recognized that a small amount of hydrazine could leak past an o-ring thereby exposing the spring to hydrazine decomposition products, i.e. ammonia. The best method for controlling stress corrosion is to select materials which are highly resistant to stress corrosion. To this end guidelines (MSFC-SPEC-522) have been prepared to aid the designer in the selection of materials for use in space booster and satellite systems. Tables II-IV are a listing of alloys grouped to show their comparative stress corrosion resistance when exposed to a sea-coast environment. Materials listed in Table II are considered resistant to stress corrosion in a seacoast atmosphere and can be used without restrictions. Materials listed in Tables III and IV should not be used unless specific evaluation and justification is made for each specific application.

In addition to ordinary atmospheric environmental effects, corrosion control procedures for space boosters and satellites must take into account other special environmental factors. Many of these are related to propellant compatibility. For instance, most organic materials are not compatible with oxygen systems. Because of lack of compatibility with LOX and stringent cleanliness requirements, organic coatings are not used on aluminum propellant tank (External Tank) interiors. Corrosion on these surfaces (2219-T87 aluminum) is prevented by use of a chemical conversion coating. In addition rigorous drying procedures are required following corrosion coating and tank cleaning (usually done in one continuous process), and the relative humidity inside the tanks is controlled to below 50%RH during storage and shipping to the launch site. The primary metallic materials not considered acceptable in oxygen systems are tin, magnesium and titanium alloys. Tin is particularly reactive, and it has been found that copper alloys with a tin content as low as 2% can react when impacted in liquid oxygen. In order to control this problem all materials used in oxygen systems must meet the requirements of NASA Handbook NHB 8060.1 at the temperature and pressure which will be encountered during use.

Propellant compatibility is also of concern in hydrogen systems, particularly at the high pressures [up to 48.3 MPa (7,000 psi)] found in the Space Shuttle Main Engine (SSME). Table V shows the effect of exposure to high pressure hydrogen on the notched strength ratio of several metal alloys. One technique which has been used to protect alloys susceptible to hydrogen environment embrittlement is by copper plating. A 0.127mm (5 mils) thick coating of electroplated copper has been used for protecting Inconel 718 in several SSME components. Gold plating [0.127mm (5 mils thick)] has also been used for this purpose on Waspaloy turbine discs. For these coatings to be effective very careful procedures are required to insure that coating adhesion and integrity are of the highest quality.

Several other propellants are encountered in space booster and satellite systems which present unique compatibility problems. The two most common are hydrazine and nitrogen tetroxide. The major concern with hydrazine systems is not corrosive attack but hydrazine decomposition. The three major metal alloys used in hydrazine systems are alloys of aluminum, stainless steel and titanium. For nitrogen tetroxide systems most metallic materials are resistant when the N_2O_4 is dry. However, since moisture can easily contaminate such systems, the primary materials of construction are those which also have high resistance to nitric acid such as the aluminum alloys, stainless steels and titanium alloys.

The criteria for selection of coatings for satellite systems are usually related to their thermal control properties and resistance to the effects of the space environment. Properties can vary widely depending upon the specific requirements needed. Figure 3 illustrates the variation in types of coatings and surface treatments which may be used. Corrosion protection properties usually are of secondary importance. Consequently, the environmental exposure conditions, particularly during manufacture and storage must be carefully controlled to prevent corrosion from occurring as well as deterioration of critical surfaces from contamination. This means stringent controls on packaging of individual components, humidity control during component assembly and environmental control during storage of completed assemblies. Since most systems are assembled in a clean room to prevent surface contamination, keeping the relative humidity below 70% should prevent most corrosion problems during the assembly process. For storage purposes, particularly long time storage, environmental conditions should be regulated so that the maximum relative humidity is below 60% and preferably below 50%. Storage in uncontrolled environments should not be allowed.

TABLE I

LIST OF STRESS CORROSION FAILURES

Alloy	Material Form	Failure Occurrence	Component Name	Program
7079-T6 Aluminum	Forging	Pre-Launch	Lox Dome	Saturn IB
AM-355 S.S.	Bar	Pre-Launch	Flared Tubing Sleeve	Saturn I
17-7PH S.S.	Sheet	Pre-Launch	Wave Spring	Saturn IB
7079-T6 Aluminum	Forging	Manufacture	PVC Support Link	Saturn V
7075-T6 Aluminum	Plate	Test	Splice Angle	Saturn V
7075-T6 Aluminum	Bar	Assembly	Pre-Valve Control Piston Cylinder	Saturn IB
2024-T4 Aluminum	Bar	Test	Oxidizer Check Valve Body	Saturn IB
17-7PH S.S.	Sheet	Test	Actuator Spring	Saturn V
17-7PH S.S.	Sheet	Test	Pre-Valve Belleville Spring	Saturn V
7178-T6 Aluminum	Forging	Storage	Upper E-Beam	Saturn IB
7079-T652 Aluminum	Forging	Storage	Rear Spar	Saturn IB
7079-T6 Aluminum	Forging	Test	Holddown Fitting	Saturn IB
7079-T6 Aluminum	Forging	Test	Actuator Body	Saturn V

TABLE II

ALLOYS WITH HIGH RESISTANCE TO STRESS CORROSION CRACKING

STEEL ALLOYS

Alloy	Condition
Carbon Steel (1000 Series)	Below 180 kis UTS
Low Alloy Steel (4130, 4340, D6AC, etc.)	Below 180 ksi UTS
Music Wire (ASTM 228)	Cold Drawn
HY-80 Steel	Quenched and Tempered
HY-130 Steel	Quenched and Tempered
HY-140 Steel	Quenched and Tempered
1095 Spring Steel	Quenched and Tempered
300 Series Stainless Steel (unsensitized)	All
21-6-9 Stainless Steel	All
Carpenter 20 Cb Stainless Steel	All
Carpenter 20 Cb-3 Stainless Steel	All
A286 Stainless Steel	All
AM350 Stainless Steel	SCT 1000 and Above
AM355 Stainless Steel	SCT 1000 and Above
Almar 362 Stainless Steel	H1000 and Above
Custom 455 Stainless Steel	H1000 and Above
15-5 PH Stainless Steel	H1000 and Above
PH 14-8 Mo Stainless Steel	CH900 and SRH950 and Above
PH 15-7 Mo Stainless Steel	CH900
17-7 PH Stainless Steel	CH900
Nitronic 33	All

ALUMINUM ALLOYS

Wrought		Cast	
Alloy	Condition	Alloy	Condition
1000 Series	All	355.0, C355	T6
2011	T8	356.0, A356.0	All
2024 Rod, Bar	T8	357.0	All
2219	T6, T8	B358.0	All
3000 Series	All	359.0	All
5000 Series	(1)	380.0, A380.0	As Cast
6000 Series	All	514.0	As Cast
7049	T73	518.0	As Cast
7149	T73	535.0	As Cast
7050	T73	A712.0, C712.0	As Cast
7075	T73		
7475	T73		

TABLE II

ALLOYS WITH HIGH RESISTANCE TO STRESS CORROSION CRACKING

(Continued)

Nickel Alloys		Copper Alloys	
Alloy	Condition	Alloy	Condition (% Cold Rolled)
Hastelloy C	All	110	37
Hastelloy X	All	170	AT, HT (2)
Incoloy 800	All	172	AT, HT (2)
Incoloy 901	All	194	37
Incoloy 903	All	195	90
Inconel 600	Annealed	230	40
Inconel 625	Annealed	422	37
Inconel 718	All	443	10
Inconel X-750	All	510	37
Monel K-500	All	521	37
Ni-Span-C 902	All	619	40
Rene 41'	All	688	40
Unitemp 212	All	706	50
Waspaloy	All	725	50, Annealed

MISCELLANEOUS ALLOYS

Wrought

Alloy	Condition
Beryllium, S-200C	Annealed
HS 25 (L605)	All
HS 188	All
MP35N	All
Titanium, 3Al-2.5V	All
Titanium, 6Al-4V	All
Titanium, 13V-11Cr-3Al	All
Magnesium, M1A	All
Magnesium, LA141	Stabilized
Magnesium, LAZ933	All

(1) High magnesium content alloys 5456, 5083, and 5086 should be used only in controlled tempers (H111, H112, H116, H117, H323, H343) for resistance to SCC and exfoliation. Alloys with magnesium content greater than 3.0 percent are not recommended for high temperature application, 66°C (150°F) and above.

(2) AT - Annealed and precipitation hardened.
HT - Work hardened and precipitation hardened.

TABLE III

ALLOYS WITH MODERATE RESISTANCE TO STRESS CORROSION CRACKING

STEEL

Alloy	Condition
Carbon Steel (1000 Series)	1240 to 1380 MPa
Low Alloy Steel (4130, 4340, D6AC, etc.)	1240 to 1380 MPa
Nitronic 32	All
Nitronic 60	All
403, 410, 416, 431 Stainless Steel	(1)
PH 13-8 Mo Stainless Steel	All
15-5PH Stainless Steel	Below H1000
17-4PH Stainless Steel	All

ALUMINUM ALLOYS

Wrought		Cast	
Alloy	Condition	Alloy	Condition
2024 Rod, Bar, Extrusion	T6, T62	319.0, A319.0	As Cast
2024 Plate, Extrusions	T8	333.0, A333.0	As Cast
2124 Plate	T8		
2048 Plate	T8		
4032	T6		
7001	T75, T76		
7049	T76		
7050	T736, T76		
7075	T76		
7175	T736, T76		
7475	T76		
7178	T76		

MAGNESIUM ALLOYS

Alloy	Condition
Magnesium, AZ31B	All
Magnesium, AK60A	All

(1) Tempering between 700 and 1100°F should be avoided because corrosion and stress corrosion resistance is lowered.

TABLE IV

ALLOYS WITH LOW RESISTANCE TO STRESS CORROSION CRACKING

STEEL

Alloy	Condition
Carbon Steel (1000 Series)	Above 1380 MPa UTS
Low Alloy Steel (4130, 4340, D6AC, etc.)	Above 1380 MPa UTS
H-11 Steel	Above 1380 MPa UTS
440C Stainless Steel	All
18 Ni Maraging Steel, 200 Grade	Aged at 900°F
18 Ni Maraging Steel, 250 Grade	Aged at 900°F
18 Ni Maraging Steel, 300 Grade	Aged at 900°F
18 Ni Maraging Steel, 350 Grade	Aged at 900°F
AM 350 Stainless Steel	Below SCT 1000
AM 355 Stainless Steel	Below SCT 1000
Custom 455 Stainless Steel	Below H1000
PH 15-7 Mo Stainless Steel	All except CH900
17-7 PH Stainless Steel	All except CH900

ALUMINUM ALLOYS

Wrought

Alloy	Condition
2011	T3, T4
2014	All
2017	All
2024	T3, T4
2024 Forging	T6, T62, T8
2024 Plate	T62
7001	T6
7039	All
7075	T6
7175	T6
7079	T6
7178	T6
7475	T6

Cast

Alloy	Condition
295.0 (195)	T6
B295.0 (B195	T6
520.0 (220)	T4
707.0 (607, Ternalloy 7)	T6
D712.0 (D612, 40E)	As Cast

COPPER ALLOYS

Alloy	Condition (% Cold Rolled)
260	50
353	50
443	40
672	50, Annealed
687	10, 40
762	A, 25, 50
766	38
770	38, 50, Annealed
782	50

MAGNESIUM ALLOYS

Alloy	Condition
AZ61A	All
AZ80A	All

TABLE V

RELATIVE RESISTANCE TO HYDROGEN EMBRITTLEMENT
NOTCHED STRENGTH RATIO (H_2/He) FOR VARIOUS ALLOYS IN HYDROGEN
AT ROOM TEMPERATURE

Alloy	K_t	Pressure MPa	(Ksi)	Ratio H_2/He
250 Maraging	8	68.9	(10)	.12
410	8	68.9	(10)	.22
1042 (Q & T)	8	68.9	(10)	.22
17-7 PH (TH 1050)	8	68.9	(10)	.23
HP 9-4-20	8	68.9	(10)	.24
H-11	8	68.9	(10)	.25
Inconel X-750	6.3	48.3	(7)	.26
Rene 41	8	68.9	(10)	.27
ED Nickel	8	68.9	(10)	.31
4140	8	68.9	(10)	.40
Inconel 718	8	68.9	(10)	.46
MP 35N	6.3	68.9	(10)	.50
440C	8	68.9	(10)	.50
Ti-6Al-4V (STA)	8	68.9	(10)	.58
Monel 400	6.3	48.3	(7)	.65
D 979 Stainless	6.3	48.3	(7)	.69
Nickel 270	8	68.9	(10)	.70
CG 27 Stainless	6.3	48.3	(7)	.72
A 515-G70	8	68.9	(10)	.73
HY 100	8	68.9	(10)	.73
A 372-IV	8	68.9	(10)	.74
1042 (Normalized)	8	68.9	(10)	.75
Inconel 625	8	34.5	(5)	.76
A517-F (T-1)	8	68.9	(10)	.77
A 533-B	8	68.9	(10)	.78
Waspaloy	6.3	48.3	(7)	.78
Ti-6Al-4V (ANN.)	8	68.9	(10)	.79
1020	8	68.9	(10)	.79
HY 80	8	68.9	(10)	.80
Inconel 706	6.3	48.3	(7)	.80
Ti-5Al-2.5Sn ELI	8	68.9	(10)	.81
ARMCO Iron	8	68.9	(10)	.86
PM Inconel 718	6.3	48.3	(7)	.86
304	8	68.9	(10)	.87
321	8	34.5	(5)	.87
Hastelloy X	8	34.5	(5)	.87
305	8	68.9	(10)	.89
Astroloy	8	34.5	(5)	.90
347	8	34.5	(5)	.91
Haynes 188	6.3	48.3	(7)	.92
304 N	6.3	103.4	(15)	.93
310	8	68.9	(10)	.93
Be-Cu (Alloy 25)	8	68.9	(10)	.93
RA 330	6.3	48.3	(7)	.95
A-286	8	68.9	(10)	.97
21-6-9	6.3	48.3	(7)	.97
7075-T73	8	68.9	(10)	.98
Incoloy 802	6.3	48.3	(7)	.99
6061-T6	8	68.9	(10)	1.00
OFHC Copper	8	68.9	(10)	1.00
316	8	68.9	(10)	1.00
Incoloy 903	8	34.5	(5)	1.00

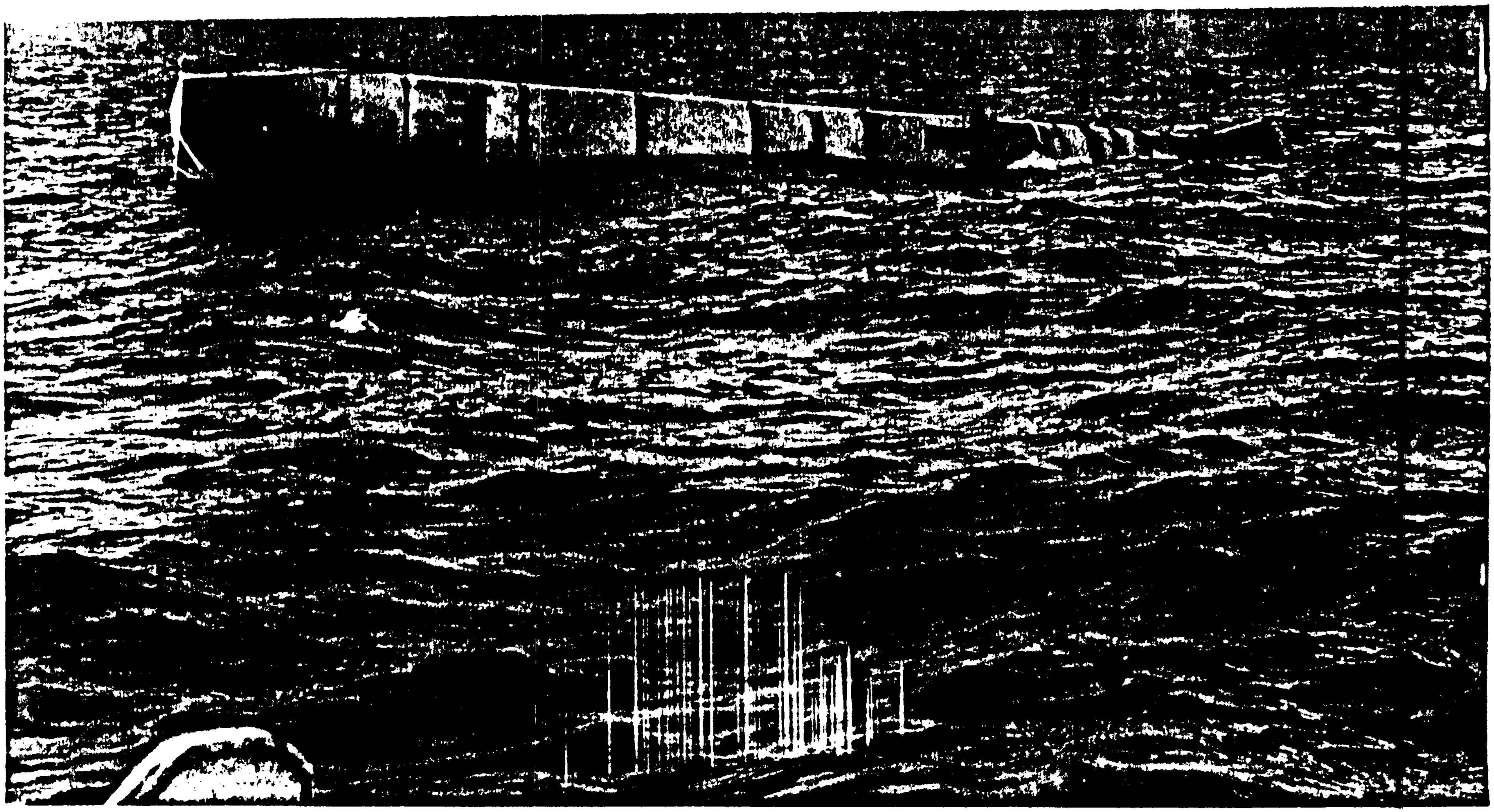

Figure 1. - Ocean Recovery of Solid Rocket Booster

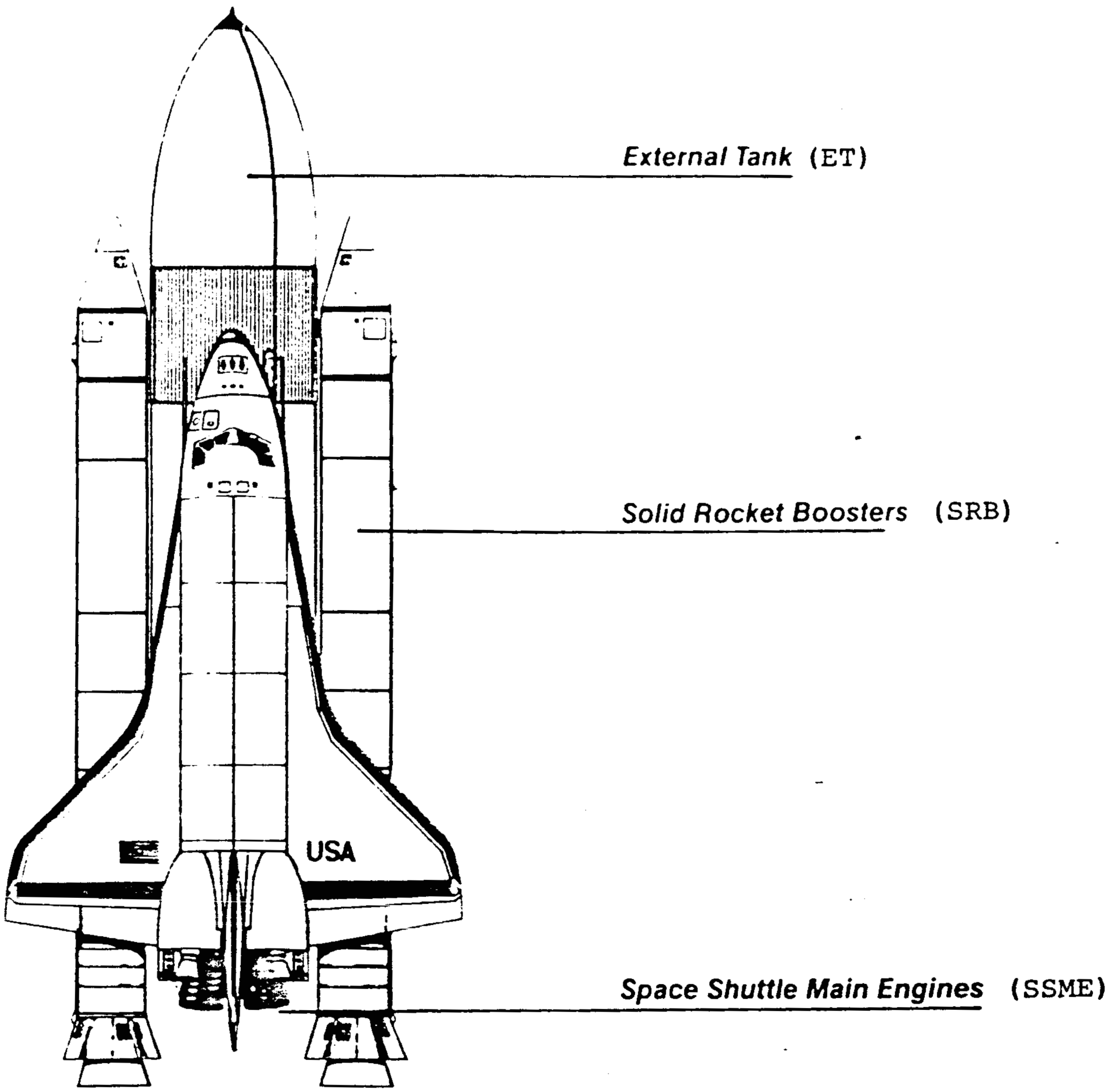

Figure 2. - Space Shuttle Propulsion System

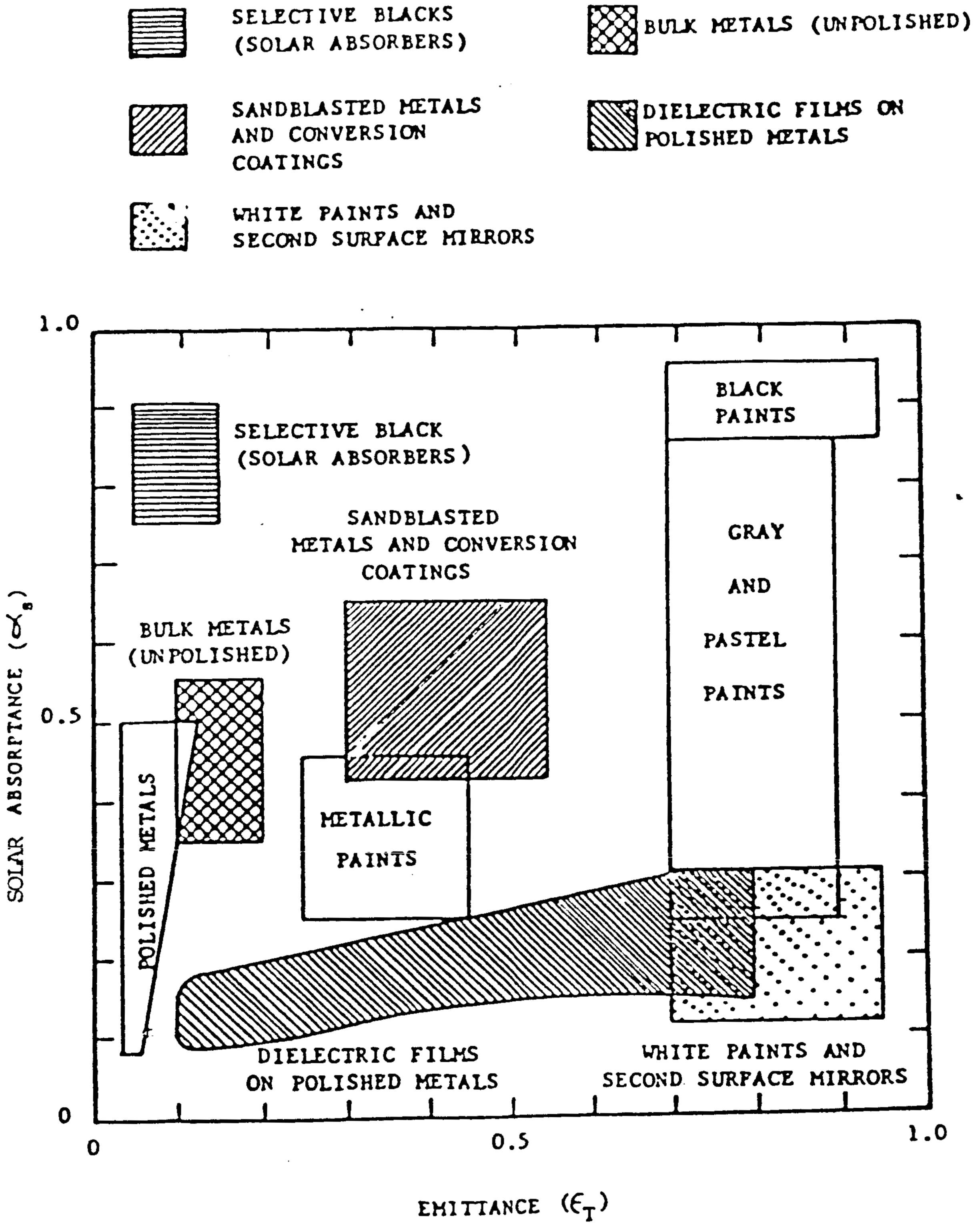

Figure 3. - Range in Optical Properties for Several Coatings and Surfaces